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One Millimeter Continuum Observations of High Redshift Quasars

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Upper limits to the one-millimeter continuum flux densities of the high redshift quasars B2 1225 + 31, Ton 490, and PHL 957 are presented. The upper limit to the power observed from these quasars at 1 mm is, on average, $\frac{1}{2}$ the observed power in the continuum at Lα. These observations are used to constrain the temperature of a hypothetical dust shell which reddens the quasar line and continuum emission by an extinction optical depth sufficient to account for the anomalously low Lα/Hα emission line ratio observed in each of these quasars. For the quasars studied, dust shell temperatures between 25 K and 50 to 95 K are prohibited by the present data. A dust shell at a temperature within this span reradiating all the power absorbed from the quasar ultraviolet continuum would produce a one-millimeter flux density greater than the measured upper limit. The average radius of the model dust shell cannot be between 70 kpc and 1 Mpc.

INTRODUCTION

For quasars the presence or absence of dust is, at present, an open question. Evidence for the existence of dust in Seyfert galaxies has been seen in their infrared energy distributions by, among others, Rieke 1978, Telesco *et al.* 1980, and Rieke and Lebofsky 1981. With respect to quasars, this question has arisen most recently because of the discrepancy between the observed flux ratios of ultraviolet, optical, and infrared hydrogen emission lines and the theoretical predictions of recombination models of ionized regions (*e.g.*, Soifer *et al.* 1981; Peutter *et al.* 1981). Reddening by dust has been proposed an an explanation for the anomalously low ultraviolet/optical line ratios of H I, He II, and O I (Netzer and Davidson 1979; Shuder and MacAlpine 1979; London 1979). On the other hand, models of the high density regions producing the broad emission lines which take into account the effects of radiative transfer and collisional processes on the energy level populations may be able to reproduce the observed line ratios for at least hydrogen without recourse to dust (Krolik and McKee 1978; Canfield and Puetter 1980; Kwan and Krolik 1981). If dust is reddening the emission from quasars it could be found on a variety of distance scales. Conceivable dust locations include the broad emission line clouds, a galaxy in which the quasar is imbedded, or the tenuous medium filling a cluster of galaxies possibly surrounding the quasar (see, for example, Davidson and Netzer 1979).

In this paper we present one millimeter wavelength observations which bear on the question of dust in three optically bright, high redshift quasars; each quasar has a measured Lα/Hα emission line ratio in disagreement by an order of magnitude with pure recombination theory. For each quasar a hypothetical dust shell is described in which all of the power removed from the intrinsic UV continuum by an amount of dust needed to explain the reddening of the emission lines is thermally reradiated at infrared through submillimeter rest wavelengths. It is shown that the present data, when analyzed within the context of this model, provide a constraint on the dust temperature and hence the location of the dust shell with respect to the quasar continuum source.

OBSERVATIONS

All of the one millimeter wavelength observations were made at the prime focus of the 5 meter Hale Telescope on Palomar Mountain. Except for the observations made in December 1979 the detector used was a composite germanium bolometer (Hauser and Notarys 1975) cooled by liquid ^{4}He to a temperature of $\sim$1.2 K. The broadband spec-

TABLE I
One millimeter observations of high redshift quasars

Object	Coordinates	Date of Observation	Redshift z^a	1 mm Rest Wavelength (μm)	$L\alpha/H\alpha^b$	Upper Limit to 1 mm Flux Density[c] (Jy)
PHL 957	0101 + 13	18 Feb 79	2.69	271	$1.8 \pm^{1.0}_{0.5}$	0.6
Ton 490	1011 + 25	08 Dec 79	1.63	380	0.8 ± 0.3	0.8
B2 1225 + 31	1225 + 31	23 Nov 80	2.19	313	0.8 ± 0.2	0.7

[a] Values from Hewitt and Burbridge (1980).
[b] Values from Soifer *et al.* (1981).
[c] The upper limits are three times the statistical uncertainty. Calibration uncertainty is 20%.

tral response of the system was between wavelengths of 600 μm and 1.5 mm. The value of the short wavelength limit stated is representative; the actual limit during a given observing session was determined by a combination of the filtering produced by cooled fluorogold (Muehlner and Weiss 1973) and the amount of water vapor present in the atmosphere on that day (Elias *et al.* 1978). The long wavelength cutoff was due largely to diffraction by the 5 meter telescope aperture. The half-power beam diameter—as defined by the entrance aperture of a lead-molded Winston light cone (Winston 1970; Harper *et al.* 1976)—was 55 arcseconds. For observations made in December 1979 the composite germanium bolometer used was cooled to ~0.3 K with liquid ^{3}He as the cryogen (Roellig 1980). In this system, a cold KRS5 filter provided the short wavelength cutoff of 750 μm and a fused silica lens was employed as field optics.

The observing procedure, data reduction process, and the method for determining the extinction in the system bandpass due to atmospheric water vapor and oxygen lines are all described in Elias *et al.* (1978). Flux density calibration at the nominal wavelength of one millimeter was accomplished using the measured brightness temperatures of Jupiter, Saturn and Mars (Werner *et al.* 1978).

RESULTS

None of the three quasars chosen for the one millimeter observations were detected. Column 7 of Table I gives the measured three sigma upper limits to the 1 mm flux density from the quasars. Because of the broad bandwidth of the system response, an index for the assumed power law flux density spectrum through the band had to be chosen to obtain the one millimeter flux density (Elias *et al.* 1978). For the upper limits presented here, the index α ($F_\nu \propto \nu^\alpha$) was taken to be 3.0 consistent with the model for the dust emission described below. If α is changed from 3.0 to 0.0 there is a 45% increase in the 1 mm flux density upper limit for PHL 957 presented in Table I: for Ton 490 the increase is 5%, while for B2 1225 + 31 it is 33%. The calibration uncertainty in the one-millimeter results is 20%. The sub-millimeter rest wavelength corresponding to an observed wavelength of 1 mm is also shown in Table I.

The observed energy distributions of the sample quasars are presented in Figure 1 as a function of the rest frequency $\nu_0 = (1 + z)\nu$ where z is the redshift shown in Table I. In Table II the continuum power density per logarithmic frequency interval (νF_ν) for the sample quasars is shown both at a wavelength of one millimeter and at the wavelength of Lα. The data of both Figure 1 and Table II indicate that the upper limit to the power observed from the quasars at 1 mm is, on average, $\frac{1}{2}$ the observed power in the continuum at Lα.

DISCUSSION

As an explanation for the observed emission line ratios, it has been suggested that dust associated

TABLE II
Power densities per logarithmic frequency interval

Object	$(\nu F_\nu)_{1mm}$ (10^{-15}Wm^{-2})	$(\nu F_\nu)_{UV}^{a}$ (10^{-15}Wm^{-2})	$\frac{(\nu F_\nu)_{1mm}}{(\nu F_\nu)_{UV}}$
PHL 957	<1.8	5.0 ± 0.3	<0.36
Ton 490	<2.4	3.3 ± 0.2	<0.73
B2 1225 + 31	<2.4	12.0 ± 0.6	<0.18

[a] The continuum flux density at Lα was used.

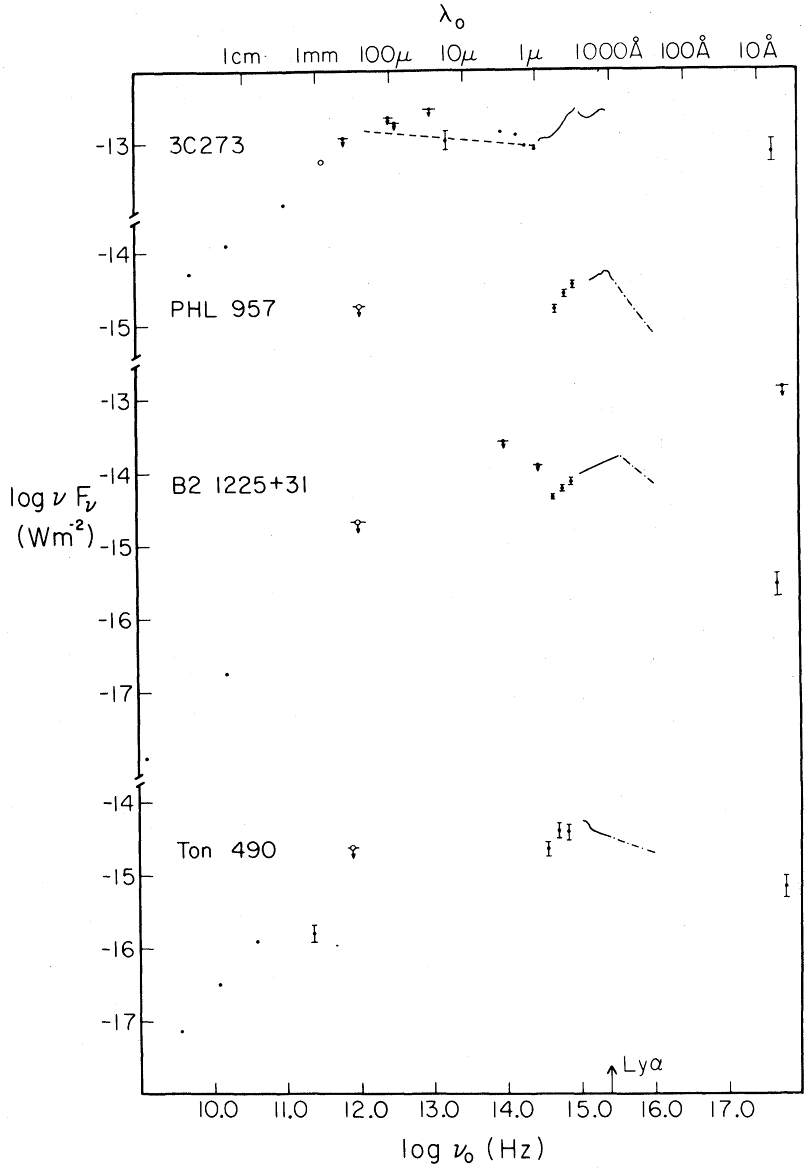

FIGURE 1 Rest frame energy distributions of three high redshift quasars and 3C273. The present data at an observed wavelength of 1 mm are the open circles. The vertical axis shows the observed power density per logarithmic frequency interval. The area under a given set of data points is proportional to the total power emitted by the quasar in that part of the electromagnetic spectrum. Dot-dash lines are the extrapolation of the observed UV continuum to a rest energy of 3 R; see text. The dashed line is a power law continuum fit to the observed infrared radiation from 3C273. Data sources—3C273: radio data, Jones *et al.* (1981); 500 μm upper limit, Hildebrand *et al.* (1977); 33, 100, 116 μm upper limits, Telesco and Harper (1979); infrared data points and visual continuum, Neugebauer *et al.* (1979); ultraviolet continuum, Boggess *et al.* (1979); X-ray data, Zamorani *et al.* (1980) PHL 957: infrared data points and visual continuum, Neugebauer *et al.* (1979), X-ray data, Ku *et al.* (1980) B2 1225 + 31: radio points, Fanti *et al.* (1975): 3.5 and 10 μm upper limits, Neugebauer (unpublished data); near infrared data points and optical continuum, Soifer *et al.* (1979), X-ray data, Zamorani *et al.* (1980) Ton 490; radio data, Owen *et al.* (1978); 90 GHz point, Swartz and Waak (1978); near infrared points, Neugebauer (unpublished data); visual continuum, Soifer *et al.* (1980), X-ray data, Ku *et al.* (1980).

with quasars reddens both the line and continuum emission (Netzer and Davidson 1979; Shuder and MacAlpine 1979). The one-millimeter data cannot exclude the presence of such dust in the quasars studied, but as will be shown below, it can restrict the dust temperature, or equivalently, the distance of dust grains from the ultraviolet radiation source of the quasar.

As a working hypothesis, dust grains will be assumed to be uniformly distributed in a shell which isotropically surrounds the regions producing the line and continuum emission; the dust reddens both regions by the same amount. The isotropy of the dust shell is a reasonable supposition since the anomalous hydrogen emission line ratios are a common occurrence in large samples of quasars (Baldwin 1977; Soifer *et al.* 1981). This model differs from the situation in which the dust is within each of the gas clouds responsible for the broad line emission (London 1979) in that the small covering factor of these clouds (Oke 1974; Baldwin *et al.* 1976) precludes such dust from significantly reddening the continuum emission.

The hypothetical dust shell—assumed to be at the single temperature T_D—will reemit the absorbed energy as modified blackbody thermal radiation Specifically, the observed one millimeter flux density, F_{1mm}, from a dust shell associated with a quasar of redshift z is given by

$$F_{1mm} = \frac{2h\nu_0^3}{c^2(1+z)^3}\frac{\tau\Omega}{e^{h\nu_0/kT_D}-1} \quad (1)$$

where ν_0 is the rest frame frequency corresponding to an observed wavelength of one millimeter, τ is the dust absorption optical depth at ν_0, and Ω is the solid angle the dust shell subtends as seen from Earth. The factor of $1/(1+z)^3$ in this expression reflects the change in the rate of photon emission $(1/(1+z))$ and the change in the solid angle of the dust shell $(1/(1+z)^2)$ in transforming the flux density from the rest frame of the quasar to the observer's frame. Dividing F_{1mm}, as given by equation (1), by the integral of the flux density over all frequencies gives

$$T_D^5[e^{h\nu_0/kT_D}-1] = \frac{2h\nu_0^4(1+z)}{c^2\sigma'}\frac{F_D}{F_{1mm}} \quad (2)$$

where F_D is the total flux radiated by the dust shell and $\sigma' = 1.44 \times 10^3 \mathrm{Wm^{-2}K^{-5}s^{-1}}$ is the analog of the Stefan-Boltzmann constant. In deriving equation (2) it has been assumed that the dust emissivity in the far-infrared through submillimeter rest wavelength range goes as λ_0^{-1}. Evidence which favors such a wavelength dependence for dust in the Galaxy is seen in the Galactic center (Gatley 1977), in molecular clouds (e.g., Evans *et al.* 1981), and in the far-infrared flux distribution observed from the carbon star IRC + 10216 (Campbell *et al.* 1976).

The measured upper limit to F_{1mm} can be used in equation (2) to provide a lower limit to the dust temperature once the total flux emitted by the grains, F_D, is determined. If the shell is heated solely by the quasar ultraviolet radiation source, F_D can be estimated from the observed emission from this source since energy conservation requires that F_D equals the flux absorbed by the dust. In calculating the heating flux, the reddening of the observed ultraviolet continuum is an important consideration. It will be assumed that the grains exhibit an extinction curve identical to that observed by Code *et al.* (1976) for Galactic dust but with the 2175 Å absorption feature arbitrarily subtracted out. It is likely that any dust grains present in quasars consist of substances not possessing this resonance; its absence in the spectra of a large sample of quasars was noted by McKee and Petrosian (1974) and Baldwin (1977). The amount of reddening the continuum is subject to can be determined from the observed hydrogen emission lines. The dust optical depth (τ_{UV}) at Lα obtained by assuming that the discrepancy between the observed Lα/Hα line ratio (shown in Table I) and its "intrinsic" case B value of 12 (Pengelly and Seaton 1962; Brocklehurst 1972) is due to reddening by this shell is given in Table III. In estimating the total UV flux absorbed by the grains, photons with rest wavelengths between 300 Å and 6000 Å were taken to effectively heat the dust (Netzer and Davidson 1979).

Substitution into equation (2) of the value for F_D evaluated in this manner and the upper limit to F_{1mm} provided by the present observations gives the limit to the dust temperature which is shown in Table III as T_2. If the reemitted flux is all in-

TABLE III
Dust model parameters

Object	τ_{UV}	T_1 (K)	T_2 (K)
PHL 957	2.4	27	57
Ton 490	3.5	21	50
B2 1225 + 31	3.5	22	95

cluded in the beam of the telescope, any dust shell must be warmer than this limit. It should be noted that this temperature bound depends solely on the ratio of one-millimeter flux density upper limit to dereddened ultraviolet flux and is independent of the choice of cosmological model.

Published observational data at extreme ultraviolet rest wavelengths for the high redshift quasars studied are lacking. It therefore was arbitrarily assumed that the measured ultraviolet continua of Ton 490 and PHL 957 could be directly extrapolated to a rest wavelength of 300 Å (3 Ry), a procedure which is consistent with the observed X-ray flux from these objects (Figure 1). In the case of B2 1225 + 31, IUE observations (Snijders *et al.* 1981 and references therein) show no detectable emission between rest wavelengths of 400 Å and 800 Å, the radiation presumably being absorbed by an intervening system at $z = 1.795$. The flux density at extreme ultraviolet rest wavelengths was obtained by interpolating between the observed data at 800 Å and the X-ray data (Tananbaum *et al.* 1979; Zamorani *et al.* 1980); directly extending the observed UV continuum to 300 Å results in a 20% increase in the calculated heating flux in this case. In dereddening these extrapolated continua it was assumed that the dust extinction optical depth is constant for $\lambda_0 <$ 1100 Å (Shuder and MacAlpine 1979); for constituents of Galactic dust, this supposition finds support in both theoretical calculations (Greenberg 1968) and laboratory measurements (Huffman 1976).

Figure 2(a) illustrates the results of applying the analysis described here to B2 1225 + 31. Comparison of the observed and dereddened ultraviolet energy distributions shows that once reddening is taken into account the hypothetical flux heating the dust grains is an order of magnitude larger than the observed ultraviolet flux. The dashed curve is the energy distribution of the thermal emission expected from the hypothetical dust shell with a temperature equal to the calculated lower limit T_2. The dust shell at this temperature radiates as much power as it absorbs from the dereddened ultraviolet continuum while producing a one-millimeter flux density equal to the observed upper limit. For dust temperatures larger than T_2 the expected emission from a shell radiating the same energy is consistent with the one millimeter upper limit.

The present observations do not rule out every temperature less than T_2 for the hypothetical dust

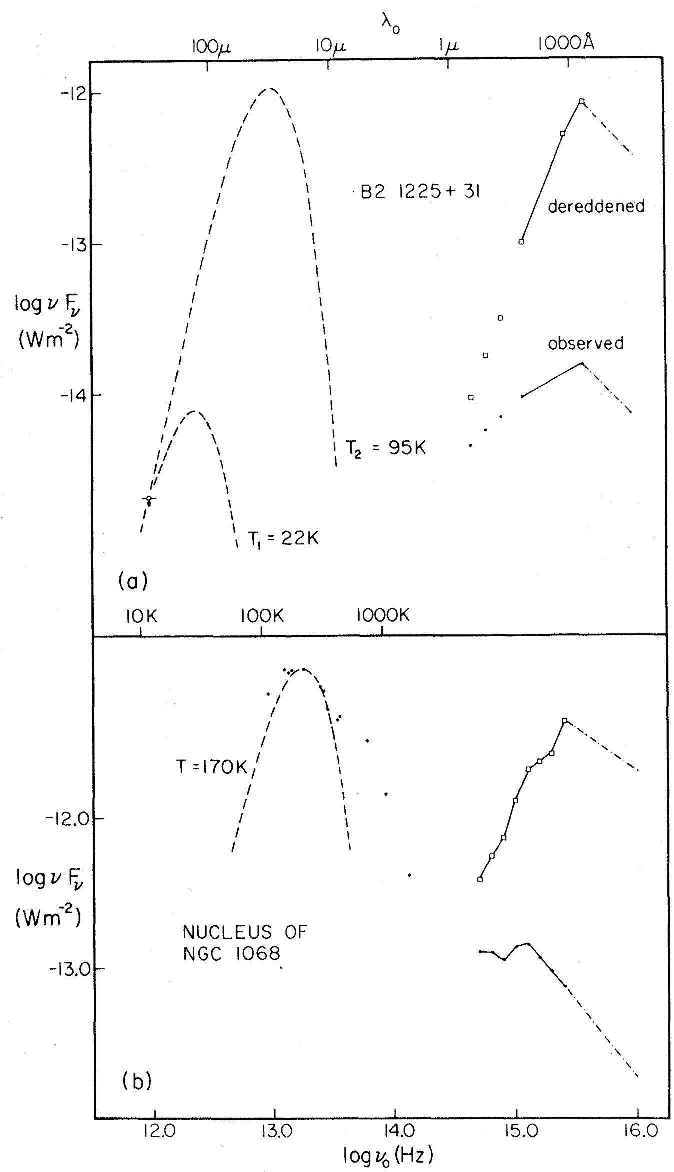

FIGURE 2 (a) Observed (solid circles) and dereddened (open squares) ultraviolet continua of B2 1225 + 31. The extrapolation of the ultraviolet continua to a rest wavelength of 300 Å are shown as dot-dash lines; see text. The dashed curves are the expected emission into a one-arcminute telescope beam from the model dust shell described in the text. Dust shells with temperatures between T_1 and T_2 would produce one-millimeter flux densities greater than the observed upper limit (open circle). The bottom scale shows the temperature of the model dust shell whose emission would peak at the given wavelength. (b) Observed infrared and ultraviolet energy distributions of the nucleus of NGC 1068 (solid circles). The dereddened ultraviolet continuum is shown as open squares. The extrapolation of the UV continua to a rest wavelength of 300 Å are shown as dash-dot lines; see text. The solid line is the energy distribution of the thermal emission from the 170 K model dust shell described in the text. Data sources—infrared points, Rieke and Low (1975); ultraviolet data, Neugebauer *et al.* (1980).

shell. At low enough dust temperatures the solid angle of the dust shell, Ω, will exceed the solid angle of the 55 arcsecond telescope beam (Ω_B) used for the present observations; in this case, the observations do not limit the total 1 mm flux density the *entire* dust shell emits and equation (2) is no longer applicable. For this situation, as expected, the 1 mm flux density observed from the dust shell will be given by equation (1) with $\Omega = \Omega_B$ since only the central 55 arcseconds of the dust shell contributes to the one millimeter flux density. Thus, if the emitting shell of dust is larger than the telescope beam the measured upper limit to F_{1mm} provides an *upper* limit to the dust temperature; this limit is presented in Table III as T_1. The observed interstellar extinction curve in the wavelength range 1100 Å to 20 μm (Johnson 1968; Code *et al.* 1976; Becklin *et al.* 1978) with a λ_0^{-1} extension for longer wavelengths has been used in calculating τ from τ_{UV}. For Galactic dust in the molecular clouds M17 and NGC 7129 the value of the far-infrared optical depth calculated from the visual extinction in this manner is in agreement with the measured value (Bechis *et al.* 1978; Gatley *et al.* 1979). The total column density of dust in the section of the shell subtended by the telescope beam has been used in determining τ. For B2 1225 + 31 the expected emission from the central arc-minute of the dust shell at temperature T_1 is also shown in Figure 2(a).

We thus conclude that the hypothetical dust shell must be at a temperature outside of the range from T_1 to T_2 in order to be in accord with the limit to its thermal emission set by the present data. The most stringent result is for B2 1225 + 31 for which dust temperatures within a 73 degree span are excluded. Uncertainties in the observed Lα/Hα emission line ratio and one-millimeter flux density upper limits produce a 20% uncertainty in the temperatures shown in Table III.

The dust temperature can be related to the radius of the shell by using the estimate of the luminosity source and the assumed grain absorption properties. In the case of B2 1225 + 31, for example, no dust shell can exist with a radius between 60 kpc and 2.2 Mpc. For the three high redshift quasars studied, the average radius of the model dust shell is either less than 70 kpc or greater than 1 Mpc. The limit of 70 kpc—the size of a compact cluster of galaxies or a giant cD galaxy (*e.g.*, Bahcall 1977)—may be the physically more relevant result. These distances take $q_0 = 1$ and $H_0 = 50$ kms^{-1}Mpc^{-1}; if $q_0 = 0$ the radii will be increased by the factor $1 + (\frac{1}{2})z$.

Observational data exist over most of the electromagnetic spectrum for 3C273 whose energy distribution is also shown in Figure 1. In addition, its emission line spectra exhibits anomalous hydrogen line ratios (Baldwin 1977; Davidsen *et al.* 1977; Boggess *et al.* 1979). It is appropriate to find if a dust shell of the type described in this paper could be reddening the line and continuum emission from 3C273. The measured Lα/Hα ratio of 1.8 (Boggess *et al.* 1979) gives a τ_{UV} of 2.4 which, when combined with the observed ultraviolet continuum, results in a UV luminosity absorbed by the hypothetical grains a factor of 7 larger than the upper limit to the total infrared luminosity between wavelengths of 1 μm and 500 μm. If, in addition, the lumniosity due to a nonthermal power law continuum (dashed line in Figure 1) known to provide a moderately good fit to the energy distribution of 3C273 (Boggess *et al.* 1979; Ulrich 1981) is subtracted from the observed infrared luminosity, the remaining power is a factor or 25 smaller than the power absorbed by the hypothetical grains. For 3C273 then, it is difficult to see how a dust shell of *any* temperature which produces the requisite reddening, could absorb all of the ultraviolet power and still reradiate flux densities consistent with all the observed near infrared through submillimeter data.

It is reasonable to ask if there is an active extragalactic object which shows evidence for a dust shell having properties similar to those discussed here. Such an object is the nucleus of the archetypal Seyfert 2 galaxy NGC 1068 whose energy distribution is shown in Figure 2(b). The dashed curve is the energy distribution of the radiation from an isothermal dust shell of temperature 170 K and a τ_{UV} of 4.1. This value for τ_{UV} is the amount of reddening necessary to produce agreement between the observed emission line intensities (Neugebauer *et al.* 1980 and references therein) and the predictions of standard Case B radiative recombination theory. This curve provides a good fit to the observed mid infrared flux densities and, as can be seen from the dereddened UV continuum, the dust shell radiates the required total flux. In addition, the angular diameter of the model dust shell is ~1 arcsecond, a value in excellent agreement with the measured size of the 10 μm nuclear source (Becklin *et al.* 1973). A more sophisticated treatment of dust emission models for the infrared radiation from the nucleus of NGC 1068 (Jones *et al.* 1977) yields similar results.

Due to the small angular size of the dust shell associated with the nucleus of NGC 1068, a fraction of the light scattered by the grains will intercept the telescope beam used for the measurements; this is in contrast to observations of radiation traversing interstellar dust clouds in which most of the scattered photons are undetected (Jones 1973; Netzer and Davidsen 1979; Neugebauer *et al.* 1980). If the equations derived by Code (1973) are used to take this effect into account in dereddening the observed UV continuum from the nucleus of NGC 1068, the ensuing value for the flux heating the grains is only 20% lower than the result obtained above using the standard interstellar extinction curve. For this calculation it was assumed that the wavelength dependence of the scattering properties of the grains present in the nucleus of NGC 1068 is the same as that exhibited by Galactic-type dust. The variation of the albedo in the ultraviolet wavelength range was taken from OAO-2 measurements of the diffuse Galactic light reported by Lillie and Witt (1976). The wavelength dependence of the mean value of the cosine of the scattering angle was taken from the calculations of White (1979) who used the mixture of grain sizes and composition determined by Mathis *et al.* (1977) to give the best fit to the observed Galactic extinction curve.

A crucial approximation of the specific model presented in this paper is that the dust grains in the shell are all at the same temperature. An alternative geometry would be a dust cloud in which there are grains at a range of radii from the central UV continuum source resulting in a distribution of grain temperatures. Qualitatively, it can be seen that a dust cloud would reradiate the power absorbed from the UV continuum over the entire span of infrared wavelengths. Rieke and Lebofsky (1981) argue that the observed radiation from the type 1 Seyfert galaxy NGC 4151 between wavelengths of 2 and 100 μm can be attributed to thermal emission from a dust cloud containing grains at temperatures between 1500 and 70 K. It would, in principle, be possible to construct a similar dust cloud model for the sample high redshift quasars in which the expected 1 mm flux density is consistent with the observed upper limits. Due to the lack of observational data between rest wavelengths of 300 μm and 3 μm for these quasars, a detailed calculation of the energy distribution of the thermal emission from such a dust cloud is not warranted at the present time.

SUMMARY AND CONCLUSIONS

This paper presents a method in which infrared observations can begin to constrain the temperature and location of dust in quasars. One-millimeter wavelength observations of three high redshift quasars with measured Lα/Hα emission line ratios considerably lower than the calculations of standard recombination theory have been reported. The upper limit to the power emitted by these quasars at an observed wavelength of 1 mm is typically half the power in the continuum at Lα. If it is assumed that an isothermal shell of dust is reddening the line and continuum emission from these quasars, analysis of the observed 1 mm upper limit constrains the physical properties of the dust. Temperatures between 25 K and 50 to 95 K (depending on the object) are ruled out for the dust shell since at temperatures within this range a dust shell emitting the requisite total luminosity would produce a 1 mm flux density greater than the measured upper limit. It is found that the average dust shell radius cannot be between 70 kpc and 1 Mpc.

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